FLA	FLAMES
PRM	PROBE
WAU	WATER-COOLED

THE OPERATION AND EVALUATION OF A WATER-COOLED ELECTRONIC IONIZATION PROBE FOR USE IN THE STUDY OF TURBULENT FLAMES

A Thesis Submitted to the
Faculty of the Graduate School of the
University of Minnesota

By

James Byron Copenhaver, Jr.

Lieutenant, United States Navy

In Partial Fulfillment of the Requirements
for the Degree of Master of Science
in Aeronautical Engineering

May, 1955

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

TABLES

PLATES

FIGURES

ACKNOWLEDGEMENTS

I wish to express my thanks to Professors N. A. Hall, L. T. Anderson, T. E. Murphy, and J. A. Wise for their advice and assistance; to Mike Schonberg and Miles Mock for their help in the construction details; and to my wife, Carmen, for her encouragement and help in preparing the manuscript.

SUMMARY

It was the purpose of this study to construct and evaluate a water-cooled electronic probe, based on a Bureau of Mines' design; to compile instructions for its use; and to indicate the proper avenues of development necessary to further the utility of the probe as a test instrument.

The probe was designed for use in the study of turbulent flames, and its operation based on the experimental fact that a zone of high ion-electron concentration exists immediately adjacent to the combustion wave. Testing of the original probe was confined to open flames. It was desired, in this study, to duplicate some of the original tests, and to extend the use of the probe to the study of flames within a combustion chamber.

During the course of the evaluation, the reliability of the probe as a flame detection device was confirmed, and it was found to be well suited for correlation studies of the sound, turbulence, and fullness of a confined flame. "Fullness" is a descriptive term referring to the extent of continuity, or the lack of breaks, in the instantaneous flame front.

Ambiguity exists in the probe response to flame fluctuations at all but very low frequencies, and the elimination of this defect requires the addition of a pulse-width discriminator or band-pass

circuit to the present configuration. The basic circuit, however, responds to signals of 20 to 20,000 cycles, indicating the high frequency potentialities of the system.

The addition of an electronic counter is desirable, should quantitative studies be undertaken, though many applications of the probe do not require this feature.

Use of a D.C. amplifier, specified in the original design, is optional in present applications of the probe.

This study was conducted by the author at the University of Minnesota, in partial fulfillment of the requirement for the degree of Master of Science in Aeronautical Engineering.

THE OPERATION AND EVALUATION OF A WATER-COOLED ELECTRONIC IONIZATION PROBE FOR USE IN THE STUDY OF TURBULENT FLAMES

INTRODUCTION

In new fields of research, a requirement is often created for specialized test instruments based on properties or behavior of the subject under study. The investigation of turbulence effects on combustion is of comparatively recent origin, and it created such a demand. An instrument was needed to corroborate the theories of turbulence advanced by Karlovitz (Reference 1); Wohl, Shore, Von Rosenberg, and Weil (Reference 2); Hottel, Williams, and Scurlock (Reference 3); and others. Bollinger and Williams (Reference 4) measured turbulent burning velocity based on a mean flame surface area, but did not take into account the turbulent fluctuations within the flame brush. A means of detecting these small-amplitude fluctuations was desirable, and their nature dictated that an electronic approach be used.

The ionization phenomenon associated with flames was investigated by Marsden (Reference 5), who charted the frequency spectra of turbulent flames and noted the relationship between electrical flame noise and turbulence. Karlovitz, Denniston, Knapschaefer, and Wells (Reference 6), engaged in research for the Bureau of Mines, became interested in the problem and began work

on an electronic probe for use as a test instrument. It was based on the experimental fact that the ionization density in the immediate vicinity of a luminous flame front is much greater than that existing in more remote regions of the combustion zone. (See Figure 1)

Figure 2, a block diagram of the probe components, shows amplifying circuits followed by a signal height discriminator and an on-off tube. Kept at a negative potential with respect to the flame, the probe wire detects a positive signal proportional to the ion-electron concentration surrounding it. This signal is amplified and modified in its travel through the circuit in such a manner that a large initial signal actuates the on-off tube. When immersed in a turbulent flame zone, the system may be adjusted to respond only to the actual contacts (large signals) of the instantaneous flame front with the probe wire. A D.C. milliammeter in the on-off tube circuit registers a current proportional to the time the flame spends off the probe.

Construction of an electronic probe, similar to the one described above, was one primary objective of the present study. This was accomplished with the aid of a basic circuit diagram and construction prints furnished by Dr. Karlovitz. Secondly, the capabilities of the probe were to be evaluated; and its suitability for further development and use as a test instrument were to be determined.
In addition, operating instructions were compiled during the evaluation studies, and are included in this report to aid follow-up investigators in becoming familiar with the probe adjustments. Circuit functions and signal analyses have been included for the same purpose.

The construction and evaluation of the electronic probe was conducted by the author during the academic year 1954-55, in partial fulfillment of the requirement for the degree of Master of Science in Aeronautical Engineering. The work was performed at the University of Minnesota, under the direction of Dr. N. A. Hall of the Department of Mechanical Engineering.

EQUIPMENT

The major equipment used in this study was the ion-sensing probe to be evaluated, with its attendant electronic circuits. Auxiliary units were: the combustion chamber, which provided an ionization source; a D.C. amplifier; a power supply; and the cathode ray oscillograph used for viewing the probe response. Plate I is an overall view of the system, and the probe components are pictured in Plates II, III, IV, and VI. Some of the construction details are portrayed in Figures 3 and 4, and in Plate V. The combustion chamber appears in Plate VI. A DuMont 304-H Oscillograph was employed throughout the tests, and is shown in the general test layout, Plate I.

Figure 3, giving the details of the probe body construction, is a reproduction of the original Bureau of Mines design. Essentially, the probe body used in this study is a duplication of this design, both in dimensions and materials. The original plans, however, specified a water passage of 1/16" drilled holes. Due to drilling difficulties in the soft copper, 1/16" grooves were milled into the bar and filled at the ends. A 1/16" copper plate, covering the milled side of the bar, was sweated into place. Outlet and inlet holes were then drilled to complete the passage. Below the water passages, a 1/8" hole was drilled through the entire length of the body to allow travel of a 3 millimeter fused-silica tube carrying the probe sensing element.

The butt of the silica tube was secured in a hard rubber button, within the probe housing, limiting the axial movement of the tube. The sensing element, a 21-gage platinum wire, was led through the silica tube to the button; and a small hole in the side of the button allowed the wire to continue to its point of connection in the preamplifier circuit. Figure 4 shows these details clearly.

The probe housing, also shown in Figure 4, was milled from a solid block of aluminum. A tapped hole for mounting the probe body was aligned with the micrometer mounting hole. The hard rubber button was fitted with a brass cap which bears against the micrometer stem, and the button is spring loaded against the micrometer. By turning the micrometer knob, the longitudinal movement of the sensing element-silica tube assembly is controlled through a 13 millimeter range. This movement can be read from the micrometer scale with an accuracy of .002 millimeters.

The preamplifier box, mounted on top of the probe housing, contains one-half of the preamplifier circuit. Plate IIa shows an overall view of the box in position, and Plate IIb shows the cover removed. Six-volt heater current and the 90-volt plate supply enter through the rear of the box by means of a power cable from the control box.

Control of all electronic functions of the probe are incorporated in the control box, Plates III and V. The front sloping panel of this box contains three switches for control of system power, two of the three protective fuses, and a flush-mounted D.C.

milliammeter. On the front vertical panel are three control knobs used for adjusting the circuits to obtain the desired information. The rear panel of the control box is open to allow access to the chassis. Six sockets are mounted on the chassis, as pictured in Plate III. Socket No. 1 is an outlet socket, and is connected through a cable to the preamplifier box. The entire power supply is fed to socket No. 2. Socket No. 3 carries the preamplifier output, and the signal returns from the D.C. amplifier through socket No. 5. A counter take-off has been provided at socket No. 4. For viewing the operating condition of the on-off tube cathode, an oscillograph is used. Socket No. 6 provides convenient terminals for this instrument.

Inside the control box, and accessible with the hinged lid open, is a screwdriver adjustment for changing the level of conduction of the on-off tube. No other adjustments are located internally.

A D.C. amplifier, Plate IV, provides the link between the preamplifier and the signal modification circuits of the probe system. For this purpose, the amplifying circuit of the BL-310 Brush Universal Strain Analyzer is used. This instrument provides in-phase amplification of the signal by a factor of seven.

The probe power supply is shown in detail in Figure 5, and in Plate V. It provides a floating potential of 90 volts, and potentials of 6, 90, and 250 volts above ground. Two 45-volt dry batteries connected in series provide the plate supply voltage for

the preamplifier. A floating supply is required, since the ground point of the preamplifier circuit is not at the low side of the voltage source.

The main power supply is provided by a single 12-volt storage battery, from which 5.3 amperes are drawn for probe operation. To prevent draining this battery, a charger is operated constantly during periods when the probe is in use. The storage battery drives a Western Electric PS-225 dynamotor, the entire output of which is imposed across a dropping resistor of 2500 ohms. Direct current voltages of 90 and 250 are tapped from this resistor to supply the plate potentials of the signal height discriminator and on-off tube respectively. A heavy-duty SPST knife switch is located on the power supply panel, to allow the dynamotor to be cut off when the probe is not in use.

Heater current for all tubes, at a potential of six volts, is drawn from the storage battery between the negative terminal and the strap connecting the third and fourth cells. Grounding the low side of the heater supply does not cause the heater-cathode maximum potential to be exceeded on any of the tubes.

A separate supply for biasing the cathode of the signal height discriminator tube is provided in the form of two 1.5 volt "A" batteries incorporated beneath the chassis of the control box. (See Plate V) In addition to this fixed cathode supply, a variable bias voltage is obtained through control knob No. 1 from the 2-volt position on the storage battery.

The power supply is controlled by means of four switches. Mentioned in a previous paragraph was the knife switch on the power supply panel. With this knife switch closed, all of the various potentials required are available at the control box. Note in Figure 5 that heater voltage and the 90-volt plate supply of the preamplifier are not affected by the knife switch. On the control box, switch No. 1 is a DPST type, and simultaneously controls heater voltage and height-discriminator tube cathode bias voltage. Switch No. 2, also a DPST type, controls the preamplifier plate supply voltage and the signal height discriminator plate voltage. Switch No. 3 controls the 250-volt supply to the plate of the on-off tube.

Three fuses guard the circuits against malfunction. The main power supply is fused at the dynamotor output with a 1/4 ampere fuse, protecting the height discriminator and on-off tube circuits. The preamplifier fuse, rated at 10 milliamperes, is located above switch No. 2 on the control box. A third fuse in series with the D.C. milliammeter, and located just above it on the control box, prevents possible overloading of the meter.

A combustion chamber was designed for the purpose of determining the capabilities of the probe in detecting combustion wave fluctuations of high frequency. The chamber, shown in Plate VI, is capable of handling approach flow velocities up to 50 feet per second. Mixing of the air and natural gas was accomplished in the lower section of the chamber by placing the gas jet at an angle to the flow direction of the air supply. A screen smoothes out the

flow and furthers the mixing process. The flame-holder was made adjustable longitudinally from a distance of three to eight inches above the jets.

The upper end of the chamber was slit lengthwise to allow the introduction of the probe at various positions along the axis. The chamber sleeve, containing a series of 5/64" holes in a helical pattern, covers this part of the combustion chamber and allows only one opening at a time to outside air. Thus the chamber slit and the sleeve orifices combine to provide a series of longitudinal test positions for the probe sensing element.

To assemble the system for operation, the components are placed in positions similar to those shown in Plate VII. The probe assembly is clamped on a suitable laboratory stand, permitting vertical positioning of this assembly. A hose connection is made between the fresh water tap and the probe body water inlet. A second hose carries the water from probe to drain. Since the probe water passages are quite small, caution must be observed in turning on the water supply, to prevent blowing the hose off its mounting. An extremely light flow of water is sufficient to prevent the probe's overheating.

Gas and air connections are made to the combustion chamber. To ignite the chamber, the air valve is opened slightly, and the gas valve is opened to its full-open position. The mixture is ignited at the top of the chamber. A gradual increase in the air flow rate makes the flame less and less stable at the top of the

chamber, until, at a sufficiently high flow rate, the flame jumps down the tube to the flame holder. At the higher air velocities, the flame sometimes continues past the flame holder to the gas inlet. This condition should be avoided, since it burns out the screen very rapidly. A distinct difference in the sound of the flame is discernible at the two flame positions.

The necessary electrical connections are shown in Figure 6. Due to socket design, it is not possible to connect the multi-wire cables improperly. One end of the 8-wire cable is permanently attached to the power supply panel, and the other end is plugged into the control box chassis. A 4-wire cable leads the necessary power to the preamplifier box, and provides the common ground lead to the control box. The positive battery lead from the power supply panel is plainly marked with a (+) on the battery clip. This lead and the similar negative one are connected to the positive and negative battery terminals. The green battery wire (two-volt height-discriminator cathode supply) is connected to the positive terminal of the first cell; and the blue wire (six-volt heater supply) is fastened to the strap midway in the chain of six battery cells.

The appropriate leads from the battery charger are connected to the positive and negative terminals of the storage battery, and the charger is plugged into the 110-volt A.C. line.

Connections may now be completed as shown in Figure 6. Grounded-shield microphone cables carry the signal to and from the

D.C. amplifier. (If the amplifier is not desired, the preamplifier output is connected directly to the signal height discriminator input terminal.) The oscillograph is connected to the socket provided on the control box. A jumper is clipped between the preamplifier box and the body of the burner to be used.

PROCEDURES AND PRINCIPLES OF OPERATION

Before any of the system power switches are actuated, it is necessary to test for proper charger polarity. If a voltage check between probe ground and a water or air pipe shows 110 volts A.C., the charger plug must be reversed. This test is made with the charger operating.

The turn-on procedure is outlined below:

1. Control knob No. 3 is set at 5 on the scale. The position of knobs No. 1 and No. 2 are immaterial.
2. The amplifier and oscillograph are turned on.
3. Switch No. 1 is turned on, and thirty seconds warm-up is allowed.
4. On the D.C. amplifier, the "D.C. gain" control is placed at eight o'clock, and the "D.C. level" control at nine o'clock. (See Plate IV)
5. The "Y-attenuator" control on the oscillograph is set at 100 on the D.C. side; "Y-amplitude" at 100.
6. The knive switch is closed.
7. Switches No. 2 and No. 3 are turned on simultaneously.

The system may now be adjusted to maximum sensitivity, prior to the circuit test. In performing this adjustment, reference is made to the D.C. milliammeter on the control box.

1. Meter reading is noted, and:
    a. If reading is zero, knob No. 3 is turned clockwise until further clockwise movement of the knob results in no change in the meter reading.
    b. If reading is not zero, knob No. 3 is turned counter-clockwise until the reading drops, and then adjusted until a maximum reading is obtained on the meter.
2. Knob No. 2 is moved from 10 to 1 on the scale, noting the milliammeter needle. If no movement of the needle is evident, knob No. 3 is moved counterclockwise until a full rotation of knob No. 2 produces a deviation of the needle from its maximum reading.
3. Knob No. 1 is placed at 10 on the scale.

The system is now set to maximum sensitivity. Ionization of relatively low intensity is adequate to reduce the meter current to zero. To check proper system operation, immerse the probe wire in the flame of a bunsen burner, the body of which is grounded to the preamplifier box. As the wire approaches the flame front, the meter current drops, reaching zero well before the probe tip enters the combustion wave.

The system may be tuned by reference to the oscillograph more rapidly than by the above procedure, but it is suggested that the

outlined procedure be followed until the oscillograph representation of the meter current is clearly in mind.

With the system adjusted to its maximum sensivitity, the on-off tube is actuated before the probe tip reaches the combustion wave. Hence the signal height discriminator must eliminate as much of the signal as necessary to make the on-off tube respond only to a contact between probe wire and flame. In theory, the proper discriminator setting should be easily ascertained. This is not the case, however, and the reasons will be discussed in a following section. At this point it is sufficient to state that counterclockwise rotation of the discriminator control increases the strength of signal required to actuate the on-off tube.

CIRCUIT FUNCTIONS

A schematic presentation of the probe circuit is given in Figure 7. The various grid potentials of the circuit are pictured graphically in Figure 8 under three conditions of operation. Reference to the two diagrams during the following explanation will aid in understanding the circuit functions.

When the system is operating near maximum sensitivity, with no flame present, a typical picture of the grid-cathode potentials is represented by Figure 8a. The probe wire, attached directly to the grid of 6J6 tube No. 1, is held at a high negative potential (-42 volts) with respect to ground. The steady output of this tube is balanced by the output of 6J6 tube No. 2, resulting in no signal

to the amplifier. The height discriminator control is set to bias the grid of that tube to a negative voltage below the cutoff value. With no current flowing in the signal height discriminator plate circuit, the on-off tube conducts at its maximum rate.

It might be noted that if the resistance of the 1000-ohm potentiometer is decreased, the preamplifier output is made more negative, resulting in the signal height discriminator tube being biased farther below its cutoff value. This adjustment has no effect on the on-off tube. An increase in the resistance of this potentiometer, however, moves the preamplifier output toward a positive value. The D.C. amplifier feeds this effect, magnified, to the signal height discriminator grid. This tube conducts, making the on-off tube grid negative. Current through the on-off tube decreases or cuts off entirely.

The circuit action as the probe wire enters a laminar flame is similar to that observed when the 1000-ohm potentiometer resistance is increased. In this case, however, control of the on-off tube grid stems from the probe wire. Positive ions gather on the wire at a rate proportional to their concentration, decreasing the negative grid potential of 6J6 tube No. 1. Figure 8b follows the signal through the circuit, showing the on-off tube biased below the cut-off point.

It is for the turbulent flame that the probe circuit is designed, one of its main functions being to discriminate between contacts of the combustion front with the probe wire, and near

approaches. Figure 1 shows the sharp increase in the ionization intensity in the immediate region of the combustion wave. By proper biasing, the height discriminator can theoretically be made to discard the signal corresponding to a near approach of the probe tip to the flame front, and yet pass the signal corresponding to a contact. Figure 8c demonstrates how this is done. In this diagram, turbulent flame signals have been imposed on the probe wire, with the stronger of these representing a flame-wire contact. The strength of the signals is increased in the original shape by the preamplifier and amplifier, and fed to the height discriminator. The larger signals cause the signal height discriminator grid potential to rise to a positive value, and in turn, cause the on-off tube to cut off. The smaller signals also cause the signal height discriminator grid potential to change in the positive direction, but not by an amount sufficient to raise the tube above the cutoff level. Consequently, there is no effect on the conducting level of the on-off tube. A counter placed in the plate circuit of the on-off tube would register only three counts, corresponding to the actual contacts between the flame and the probe tip.

In the test apparatus used during this investigation, the effect of controls 1, 2, and 3, on signal height discriminator grid are as follows:

6 ohm pot. - .200 volts per division

25 ohm pot. - .0502 volts per division

1000 ohm pot. - .736 volts per division

A "D.C. Centering" control on the amplifier used performs essentially the same function as does the 1000-ohm potentiometer.

In the cathode circuit of the on-off tube, a D.C. milliammeter measures the current. A large capacitance bridges the ammeter contacts. When the probe wire approaches a laminar flame, the on-off tube grid is biased in the negative direction, decreasing the on-off tube current. The capacitance serves no purpose. When the probe tip is placed in a highly turbulent flame, however, a series of rapid "no-current", "full-current" conditions result in the on-off tube cathode circuit. Due to the high storage capacity of the averaging condenser, the D.C. meter reads an average value of current. The on-off tube is fully conducting during the periods when the probe wire is not in contact with the combustion wave; and does not conduct while the probe wire and flame are in contact. Hence the meter reading corresponds to the fraction of time the probe wire is not in the flame front.

The plate potential of the on-off tube is controlled by a 25,000-ohm potentiometer. The setting of the potentiometer determines the level of conduction for this tube for any given grid potential. When the potentiometer is adjusted for a high plate voltage, a stronger negative signal must be impressed on the grid to cause the tube to cut off.

TESTING PROCEDURES

In general, the procedures used in testing the utility of the probe were qualitative, and quite simple. In correlating flame-noise, fullness, and turbulence, visual and aural observations of the flame were made concurrently with on-off tube current readings. Observations of the flame length and time contour in the closed combustion tube were made by inserting the probe at various stations downstream from the flame holder.

Two quantitative tests were made. The relative ion-electron concentration at points in and near a laminar front was measured, and the circuit response to a signal of constant amplitude was charted at frequencies of 20 to 2,000 cycles. The capabilities and defects of the probe circuit brought to light by these tests are discussed fully in the following section.

RESULTS AND DISCUSSION

A survey was made of the ion-electron concentration in the vicinity of a laminar flame front, for the purpose of comparing probe response with that obtained in the original experiments by the Bureau of Mines. In carrying out this survey, the on-off tube current was recorded as a function of probe position, tabulated in Table I, and plotted on Figure 9. The slope of this curve was computed on a 0.2 millimeter increment of probe advance and plotted as ion-electron concentration on Figure 10. Superimposed on this figure is a reproduction of the similar curve obtained at the Bureau of Mines.

As a result of probe configuration, difficulty was experienced in obtaining data of sufficient accuracy for the laminar flame survey. The meter is accurate to one decimal, with the second place estimated; and multiplication of error in ensuing computations produced a 17 unit vertical displacement of the ionization curve for a unit error in the second decimal place. This error was compensated somewhat by plotting first the meter current, Figure 9, and computing the slope of this curve rather than utilizing the actual increments of meter current observed with the advance of the probe.

The second factor affecting the accuracy lay in the inadequate meter capacitance built into the system. Even in a laminar flame there is a very low frequency swaying of the flame front, on the order of two cycles per second. The meter capacitance of 8000 microfarads effectively damps the needle in flames of low turbulence intensity (20 cycles), but is inadequate for the elimination of the very low frequency variation of the laminar front. This system characteristic made it necessary to average the meter readings by eye, and second decimal place inaccuracy resulted.

It might be noted that a third source of error would be encountered in operating at either extreme of the normal meter readings. The characteristic curve of 6SL7 plate current is non-linear below 0.4 milliamperes. This non-linear effect is transmitted to the on-off tube; at low values of current by the characteristic of the on-off tube itself, and at values near full-on by the characteristic of the height discriminator. The magnitude of the error

thus created is negligible in comparison to the former two in laminar flame study, but becomes evident at high frequency levels (Figure 13).

Figure 10 shows good correlation between the two curves during the concentration buildup prior to entering the flame front. Within the flame front, however, the dotted curve shows a sharper decrease in concentration as the probe moves toward the unburned gas side. In seeking an explanation for this departure, the thickness of the flame brush was measured as accurately as possible. One millimeter was the average of several measurements. It may be noted from Figure 10 that the combustion wave width measured by the Bureau of Mines experimenters is approximately one-half millimeter. Since the measurements performed in this study were made on a very low intensity flame, the difference in front width is reasonable; and this difference satisfactorily accounts for the departure between the two curves of Figure 10.

The frequency response of the system was checked at the preamplifier output and at the on-off tube. Results of these checks may be found in Figures 11, 12, and 13.

The tests were conducted with an audio signal generator, which was connected across the 0.47 megohm resistance at the probe wire. A 3.3 megohm resistance was used to attenuate the oscillator output to a usuable quantity.

The preamplifier response, Figure 11, shows that circuit to have a relatively constant amplification under 600 cycles, the region of primary interest. Another constant amplification region

extends from 4000 cycles to 20,000 cycles, and a non-linear portion exists between these two regions. This distortion in the preamplifier output produces little net effect on the system. Figure 12a is a reproduction of one known frequency spectrum, and curve (b) shows the preamplifier effect on this spectrum. Frequencies in the 500-4000 cycle range receive a greater boost than those at lower frequencies, but signal strength decreases so rapidly with rising frequency that at normal height discriminator settings these higher frequencies are eliminated, regardless of the increased amplification.

On-off tube response to a signal of uniform amplitude is shown in Figure 13. This sequence of oscillograph sketches is indicative of the gradual change in the wave shape of on-off tube current through the 20-20,000 cycle range. Response at the higher values of frequency is of no consequence in the present application of the probe to turbulent flame study, but does show the system potentialities, should it be desired to utilize it in another field.

The function of the signal height discriminator control lies in the discarding of low amplitude signals. It performs this function satisfactorily, but there is no assurance that it eliminates only the unwanted signals. Unfortunately, there are two causes of differing signal height. The sharp increase in ion-electron concentration in the immediate region of the combustion wave results in a differentiation by the probe circuit between flame contacts and near approaches of waves at one frequency; but a near approach of a low frequency wave may give the same signal strength as an

actual contact by a wave of higher frequency. This latter effect is due to the decreased signal strength of higher frequency components. (See Figure 12a) It is possible to conclude that at some high setting of the discriminator control, the system will register only wave contacts of the lower frequency components, but no definite line can be drawn.

In a turbulent flame, the high frequency components contain only a small fraction of the total turbulent energy (Reference 6), and may be eliminated without invalidating the results. A pulse width discriminator circuit should be inserted for this purpose. If it does become desirable to study the higher frequency components, a band-pass circuit will be necessary. As shown in Figure 13, the probe circuit is capable of handling any desired frequency below 20,000 cycles.

The probe circuit, as developed by the Bureau of Mines, contained a commercial electronic counter for the purpose of recording the number of contacts of the flame front with the probe wire in a specified length of time. Preliminary testing of the probe was conducted in a laminar flame vibrated by sound waves of a known frequency, and the measured maximum velocity of the flame front was compared with the computed value, showing close correlation. In these tests, the flame front was essentially perpendicular to the probe axis at all times. In the turbulent flame, however, the probe-measured velocity was greatly in excess of the estimated turbulent burning velocity, and no correlation between the two could be

obtained. High velocity components in oblique directions to the probe wire account for the departure from the expected values, and since these components are random, the probe is not useful in measuring the velocity of turbulent flame front fluctuations.

Many studies based on probe observations may be carried out without the use of a counter, but it is essential for band-pass studies, or for frequency studies of a more general nature.

The control box panel contains a counter tap, but should it be desired to add a counter to the circuit, a pulse-sharpening circuit must be inserted between the control box and the counter used. An alternate method of pulse counting, and perhaps a better one for occasional application, is that of strip film recording of the oscillograph face.

The D.C. amplifier introduced a small-amplitude alternating current, of 1920 cycles per second. The effect of this unwanted signal on the operating characteristics of the system was not noticeable; nevertheless, it was desired to remove it in order to achieve a pure signal at the on-off tube. In one attempt to eliminate the signal, the D.C. amplifier was removed from the system entirely, and it was subsequently ascertained that satisfactory system operation could be achieved without it. Observations were made with and without the amplifier, and it was noted that a steeper cut-off at the on-off tube was the only desirable contribution of the amplifier. Meter readings, however, were not measurably affected by the inclusion or exclusion of the amplifier. It was concluded that

the amplifier is not essential to probe operation in the range of primary interest in present turbulence studies, that of the lower frequencies.

In the study of ducted flames, the probe is ideally suited for correlating the length of a turbulent flame with turbulence intensity, approach-flow velocity, flame-holder configuration, and other factors. If the area downstream of the flame-holder is probed, the maximum length of the combustion zone may be readily determined. Figure 14 shows the result of one such test. The probe was inserted at stations one centimeter apart downstream of the flame-holder. The resulting meter readings are proportional to the fraction of the total time the flame spent off the probe. It may be noted from the curves that combustion is complete 8.7 to 9.7 centimeters downstream from the flame-holder, with the longer flame corresponding to the lower flow velocity. Similar tests, covering a large variety of flame parameters, could be easily devised and executed.

An immediate application of flame length determination might be made in the testing of turbojet engines. Turbine blades fail quite rapidly when the combustion wave impinges directly on them, making it desirable to contain the actual combustion process well ahead of the turbine wheel. The electronic probe, with its ability to discriminate between the actual combustion wave and the surrounding hot gas flow, is an ideal flame detector, and could be utilized to give a visual indication or to actuate an automatic control.

The interrelation among three phenomena associated with flames may be observed with the electronic probe. The turbulence, the

sound, and the "fullness" of a flame are closely related. A turbulent flame appears to the eye as a continuous wall of combustion, but observations with the electronic probe show that this is not the case. With the probe wire pushed completely through the flame brush, a small current continues to flow in the on-off circuit. Since this current is proportional to the fraction of time the instantaneous flame front is not in contact with the probe, it is evident that the flame is discontinuous. Karlovitz, Reference (6), has advanced the theory that the combustion wave consists of a number of small volumes of explosive mixture, with spaces between, and the theory is well borne out by the probe observation. The term "fullness", referring to the flame, describes the degree to which the combustion wave is continuous.

In observing the correlation among turbulence, noise, and fullness, the probe is pushed through the flame brush within the compressed air combustion chamber, and the air supply is gradually increased. That turbulence increases with the increased air flow may be observed visually. Flame sound also becomes more intense with the larger air flow. On-off tube current observed on the meter gradually increases, showing the flame discontinuities to be increasing. Noise and meter current reach a maximum just before flame blowout.

A more quantitative study of the relation between flame noise and fullness might prove valuable in furthering the knowledge of turbulent flame propagation. Such a study could be carried out using

the electronic probe in conjunction with a decibel meter. Ultimately, the knowledge might be applied in the study of "screech", a destructive form of combustion sometimes encountered in ramjets.

Throughout the study, there was no breakdown of the probe system, either mechanical or electrical. The electrical aspects of the system have been thoroughly treated; but there is also one mechanical aspect worthy of note, the water-cooled probe body. Without this protection, a very few minutes of operation in a high temperature zone would result in breakdown of the electronic circuit in the preamplifier box. The cooling system was tested by immersing the probe body in the flame of a bunsen burner. It was noted that the water jacket, probe housing, and preamplifier box remained cool enough to touch, indefinitely.

CONCLUSIONS AND RECOMMENDATIONS

1. The probe is completely reliable as a means of flame detection.
2. The probe is applicable in its present configuration to correlation studies of flame sound, fullness, and turbulence.
3. The probe is suitable in its present configuration for use in flame mapping.
4. The D.C. amplifier is not an essential component of the system, if the study is limited to low-frequency, high-amplitude fluctuations of a flame front.
5. The D.C. amplifier is essential for studying bands of higher frequency, low-amplitude signals.

6. System operation in the present application is not seriously affected by the non-linear preamplifier output.

7. With band selection circuits added, the probe is suitable for the study of any range of frequencies up to 20,000 cycles per second.

8. A pulse width discriminator circuit is essential for quantitative studies on turbulent flames, for the purpose of removing the ambiguity of probe response.

9. The cooling system of the probe is adequate for indefinite periods of probe operation in regions of high temperature.

10. To increase the utility of the probe as a general test instrument, an electronic counter is desirable. For quantitative studies, it is essential.

11. For studies of extremely low frequency flame variations (below 15 cycles) a meter shunt capacitance on the order of 20,000 microfarads will be required.

12. The accuracy of probe observations may be improved by the substitution of a large scale, 0-2 milliampere meter in the on-off tube circuit.

REFERENCES

1. Karlovitz, B., "Open Turbulent Flames", Fourth International Symposium on Combustion, p. 60. Williams and Wilkins Company, Baltimore, Maryland. 1953.

2. Wohl, K., Shore, L., Von Rosenberg, H., and Weil, C. W., "The Burning Velocity of Turbulent Flames", Fourth International Symposium on Combustion, p. 620. Williams and Wilkins Company, Baltimore, Maryland. 1953.

3. Williams, G. C., Hottel, H. C., and Scurlock, A. C., "Flame and Explosion Phenomena", Third Symposium on Combustion, p. 21. Williams and Wilkins Company, Baltimore, Maryland. 1949.

4. Bollinger, L. M., and Williams, D. T., NACA Technical Note No. 1707. 1948.

5. Marsden, R. S., Jr., "The Electrical Noise of Turbulent Flames", Fourth International Symposium on Combustion, p. 683. Williams and Wilkins Company, Baltimore, Maryland. 1953.

6. Karlovitz, B., Denniston, D. W., Knapschafer, D. H., and Wells, F. E., "Studies on Turbulent Flames", Fourth International Symposium on Combustion, p. 613. Williams and Wilkins Company, Baltimore, Maryland. 1953.

Table I. Laminar Flame Survey

No.	X MM	I MA	I_1 MA	ΔI_1 MA	F	ΔI_1 Arbitrary
1	12.5	1.10			1725	
2	12.0	1.10	1.10	0		0
3	11.6		1.096	.004		6.9
4	11.5	1.095				
5	11.4		1.094	.002		3.45
6	11.2		1.092	.002		3.45
7	11.0	1.09	1.089	.003		5.17
8	10.8		1.086	.003		5.17
9	10.6		1.082	.004		6.9
10	10.5	1.08				
11	10.4		1.079	.003		5.17
12	10.2		1.075	.003		5.17
13	10.0	1.07	1.071	.004		6.9
14	9.8		1.067	.004		6.9
15	9.6		1.062	.005		8.63
16	9.5	1.06				
17	9.4		1.058	.004		6.9
18	9.2		1.054	.004		6.9
19	9.0	1.05	1.046	.008		13.8
20	8.8		1.038	.008		13.8
21	8.6		1.026	.012		20.7
22	8.5	1.02				
23	8.4		1.013	.013		22.4
24	8.2		.998	.015		25.9
25	8.0	.98	.982	.016		27.6
26	7.8		.966	.016		27.6
27	7.6		.949	.017		29.3
28	7.5	.94				
29	7.4		.922	.027		46.5
30	7.2		.870	.052		89.6
31	7.0	.81	.812	.058		100
32	6.8	.76	.760	.052		89.6
33	6.6	.72	.710	.050		86.3
34	6.4	.65	.656	.054		93.1
35	6.2	.61	.610	.046		79.4

Table I. Laminar Flame Survey (Cont.)

No.	X MM	I MA	I_1 MA	ΔI_1 MA	F	ΔI_1 Arbitrary
36	6.0	.57	.576	.034		58.6
37	5.8	.56	.557	.019		32.8
38	5.6	.55	.542	.015		25.9
39	5.4	.53	.532	.010		19.0
40	5.2	.525	.525	.007		12.1
41	5.0	.515	.520	.005		8.63

Legend: X = Probe position

I = On-off meter current

I_1 = Averaged meter current from Figure 9

I = $(I_1)_X - (I_1)_{X + 0.2\ mm}$

F = Arbitrary factor, derived as follows:

Let $(\Delta I_1)_{max}$ = 100 arbitrary units

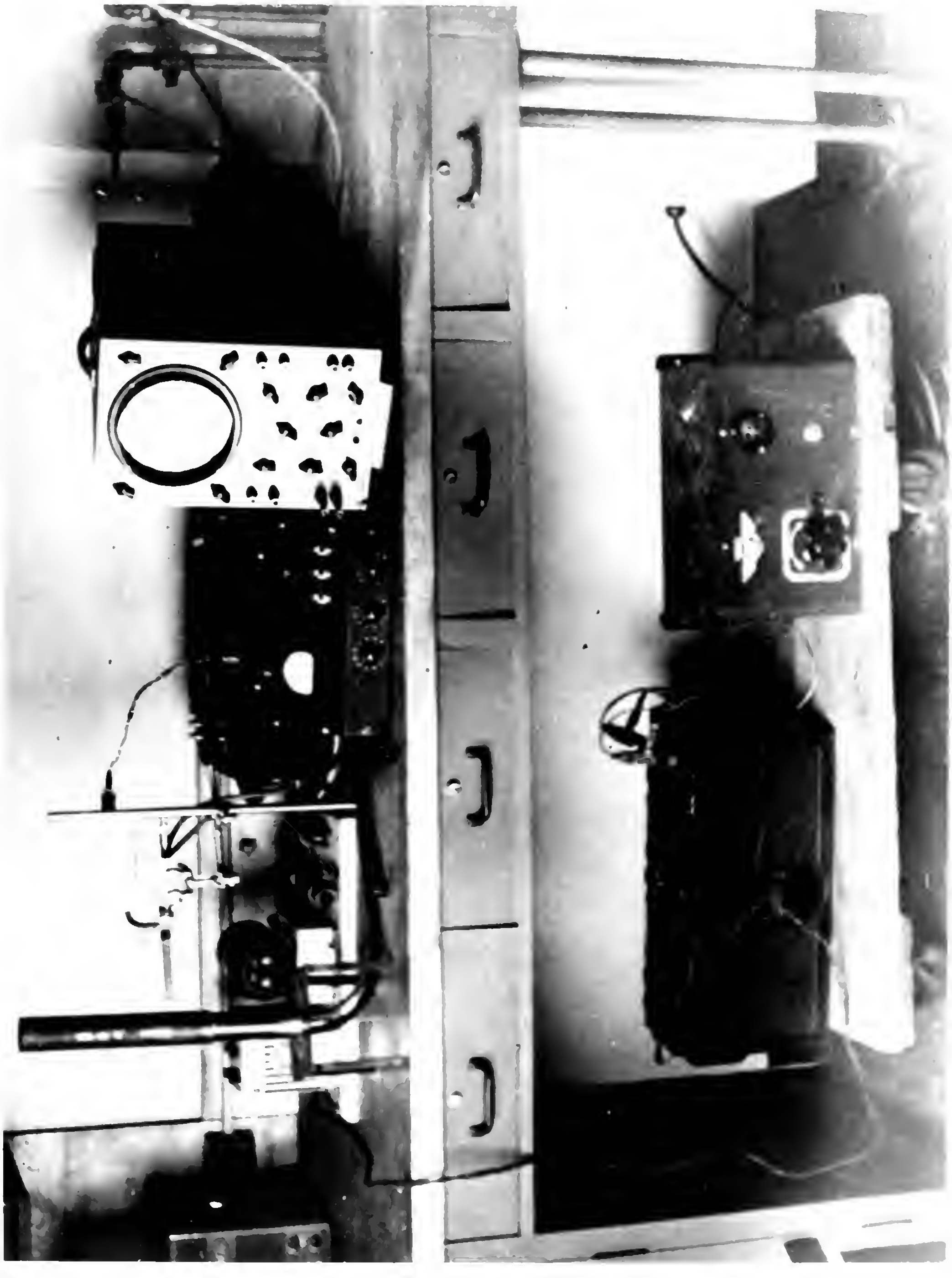
$(\Delta I_1)_{max}$ = .058 MA at X = 7.0

.058 F = 100

F = 1725

Table II. Preamplifier Frequency Response

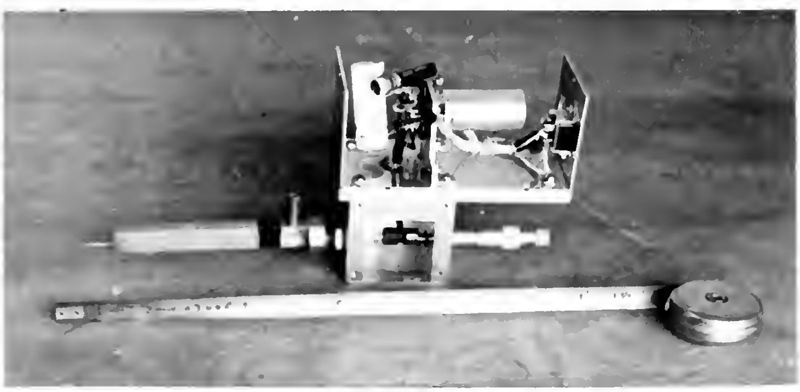
No.	Frequency Cycles/Sec	Response Spaces	Oscillograph Factor Volts/Space	Response Volts
1	20	12.5	0.28	.35
2	100	10		.28
3	200	10.5		.29
4	300	12		.34
5	400	8.5		.24
6	600	10.5		.29
7	800	16.5		.46
8	1,000	21.5		.60
9	1,200	23.5		.66
10	2,000	21.5		.60
11	4,000	15.5		.43
12	10,000	14.1		.39
13	20,000	14.0		.39



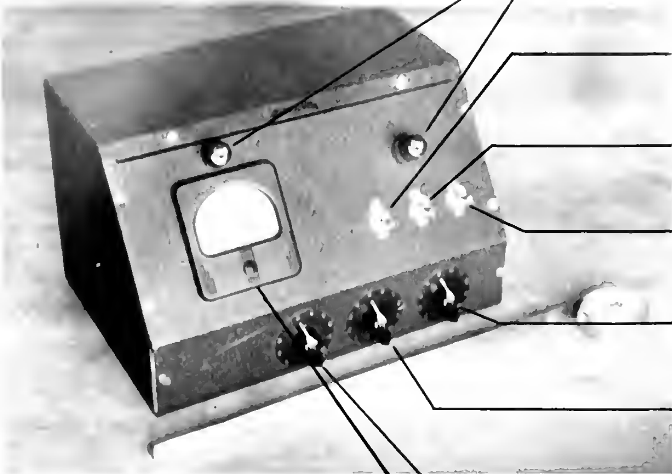
Electronic Probe, Component Layout

PLATE I

a. Probe, assembled

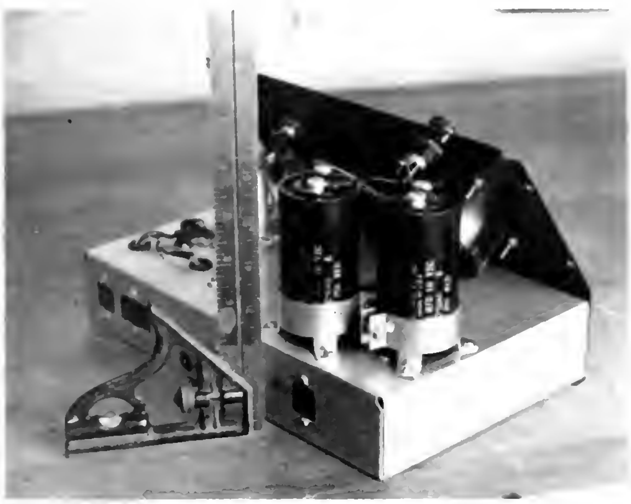


b. Internal view of the probe assembly, showing the positioning mechanism and the arrangement of preamplifier circuit components



a. Control Box.

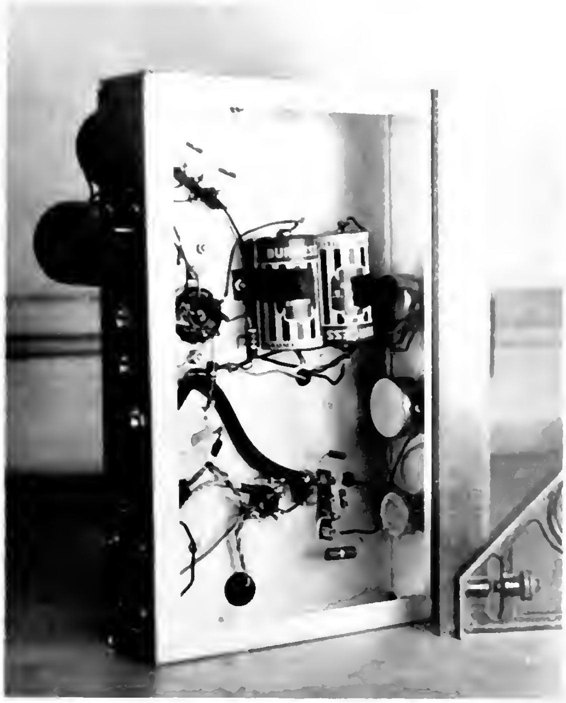
b. Rear panel of Control Box



c. Interior of Control Box, showing the high capacity averaging condensers

a. Top view of amplifier, showing the operating controls

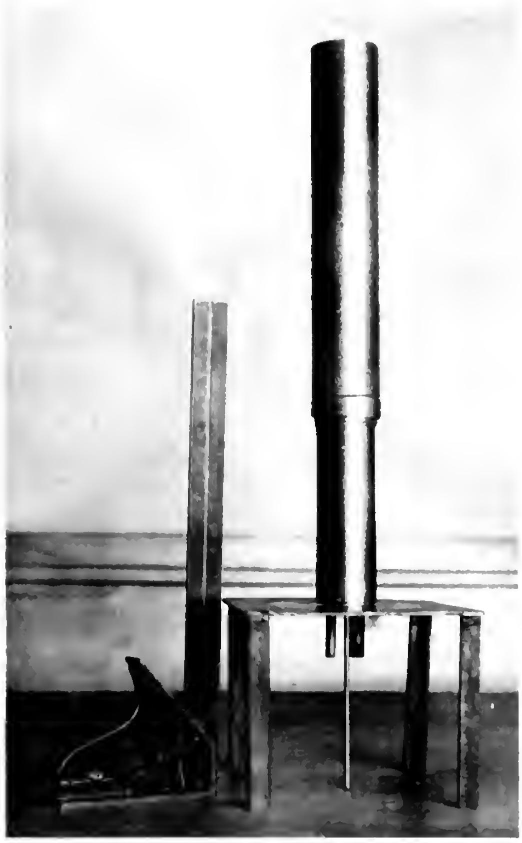
b. Rear view of amplifier, showing the terminals utilized



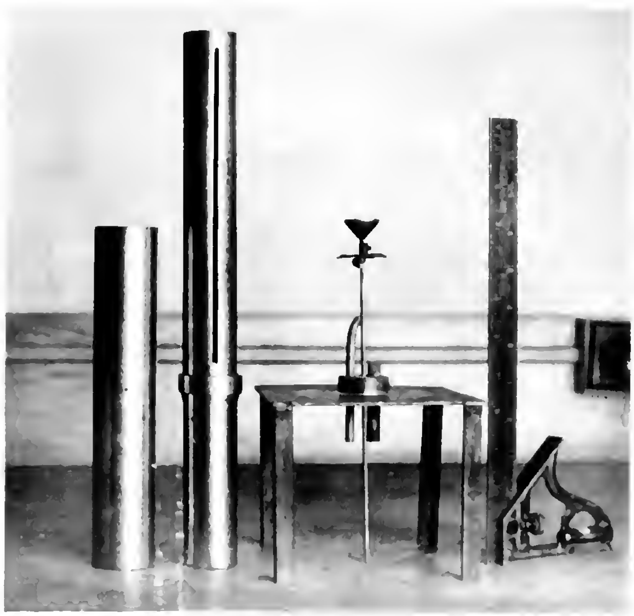
a. Bottom view of Control Box, showing signal height discriminator bias batteries

b. Probe Power Supply

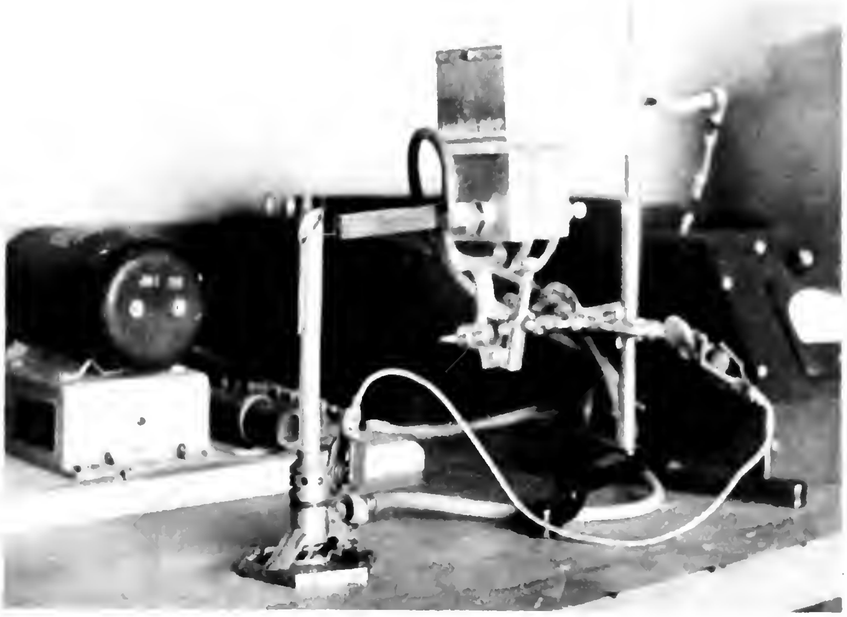
PLATE V



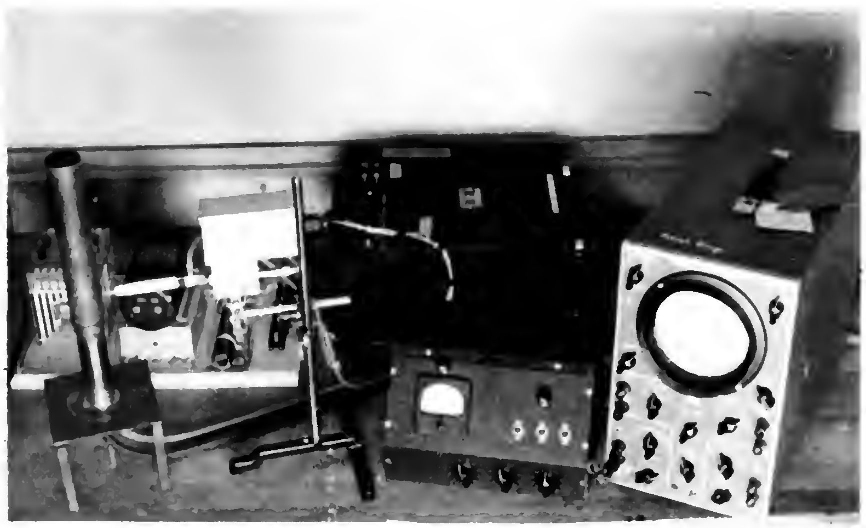
a. Combustion Chamber



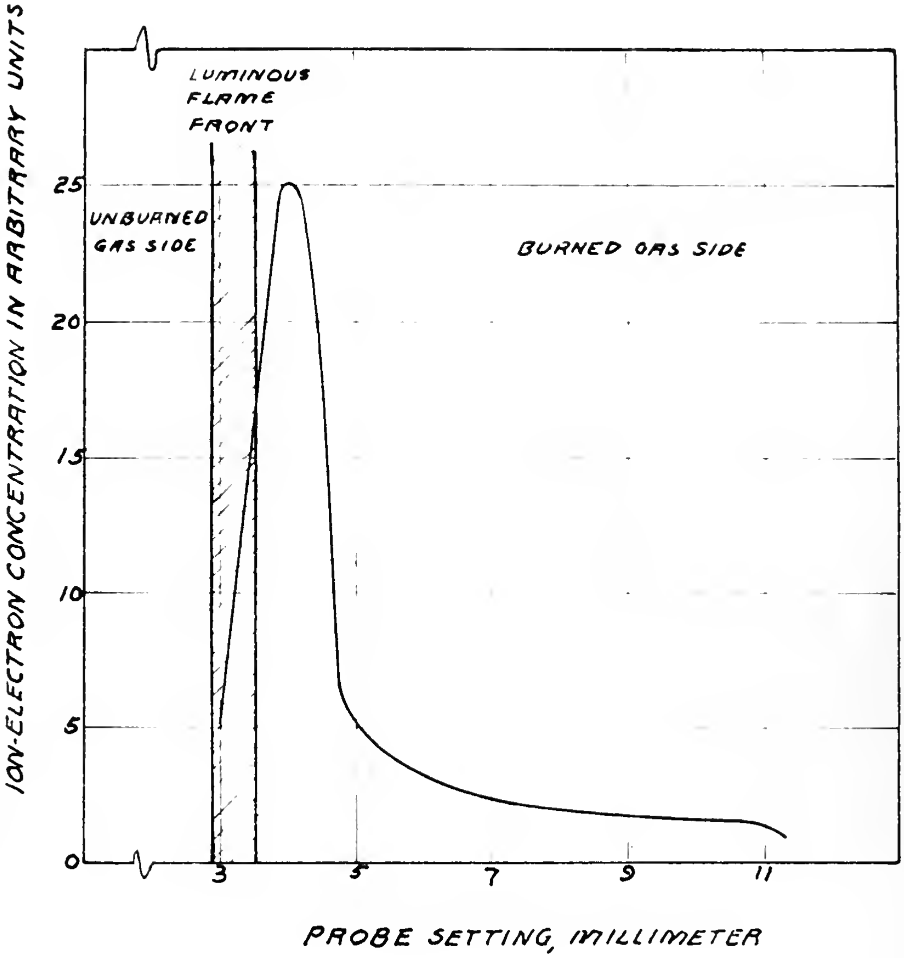
b. Combustion Chamber Assembly



a. Probe and burner arrangement for survey of a laminar flame, showing the burner shroud in place for approach from the unburned gas side



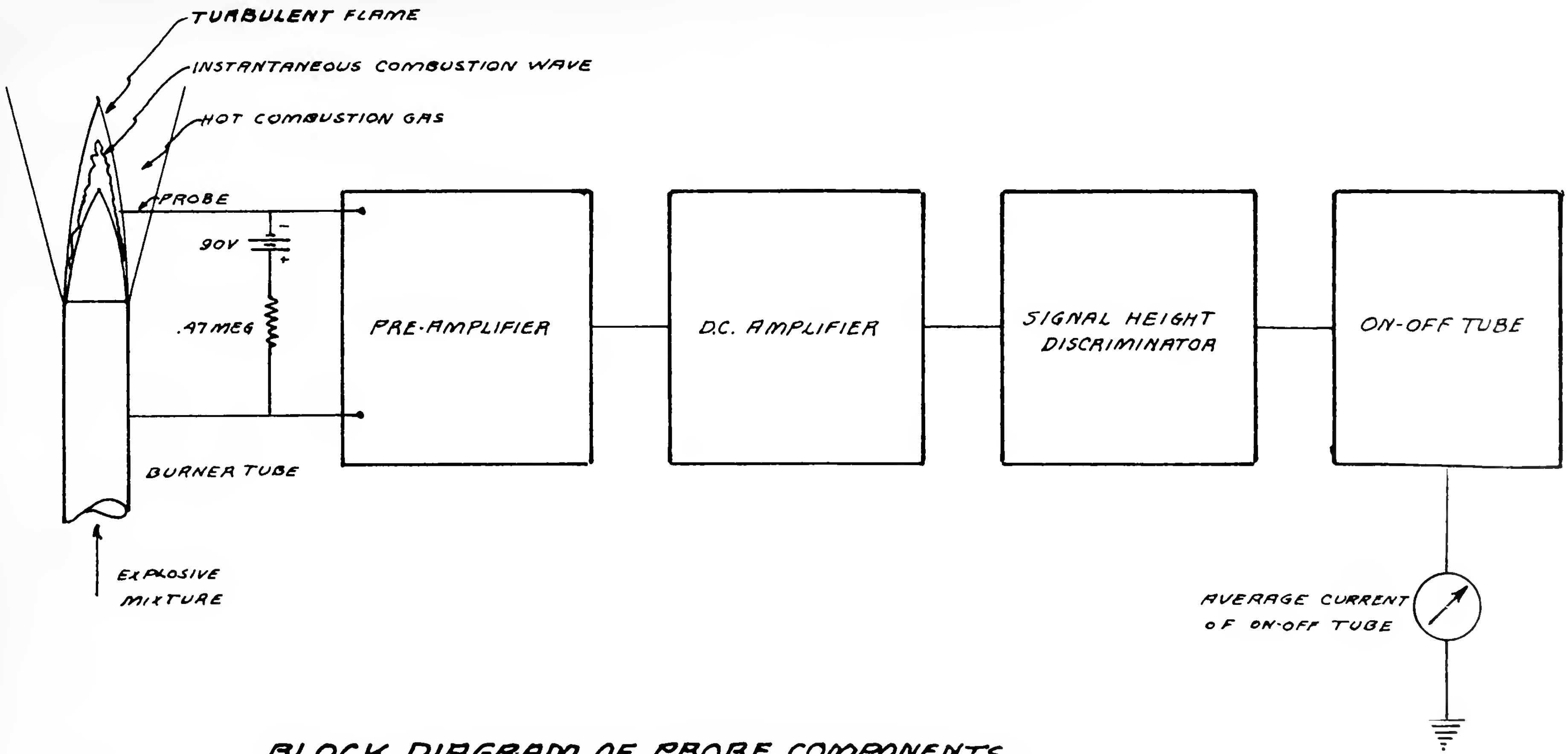
b. System components arranged for oper- with a turbulent flame



DISTRIBUTION OF ION-ELECTRON CONCENTRATION IN & NEAR A LAMINAR FLAME FRONT
(REPRODUCTION OF FIG. 6, REF. 6)

FIG. 1

12-9-54 JBC



BLOCK DIAGRAM OF PROBE COMPONENTS

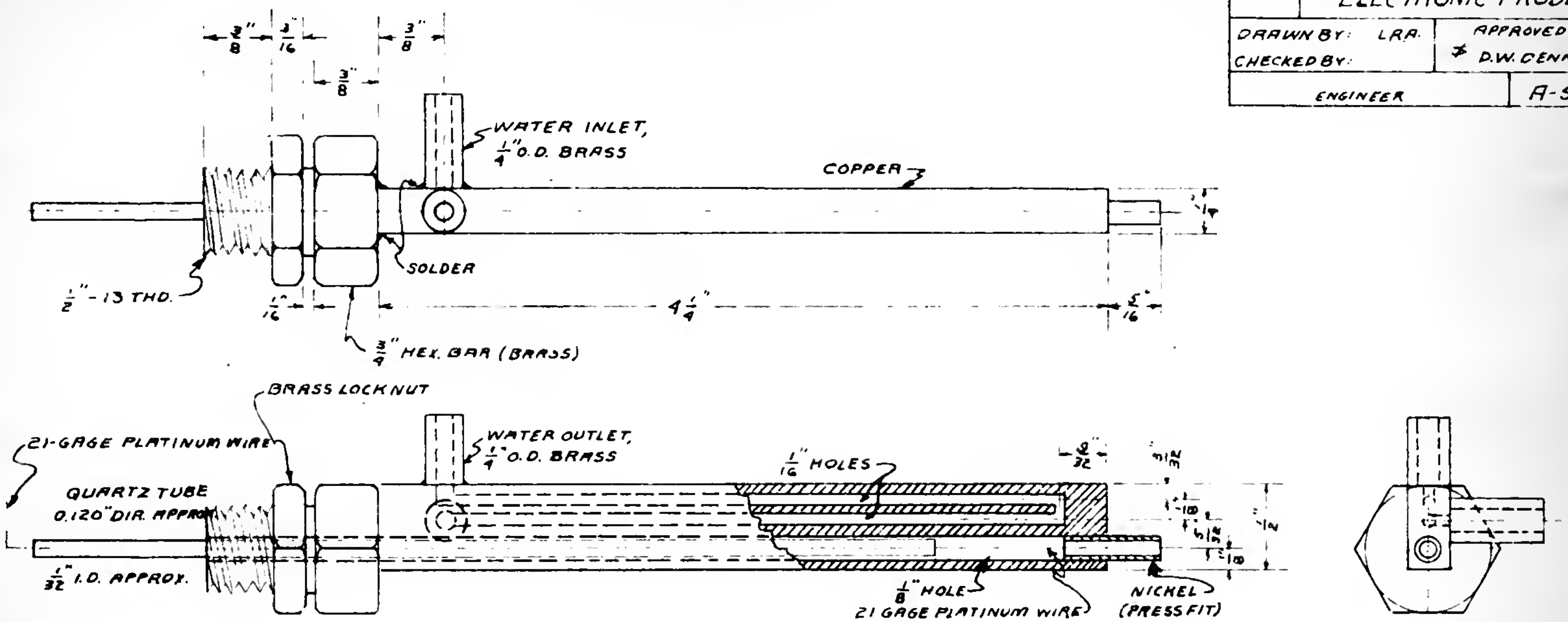
(FROM FIG. 7 OF REF 6.)

FIG. 2

12-10-54 JBC

BUREAU OF MINES PITTSBURGH, PA

DATE 1-13-54	WATER-COOLED ELECTRONIC PROBE
DRAWN BY: LRA. CHECKED BY:	APPROVED D.W. DENNISTON
ENGINEER	A-520



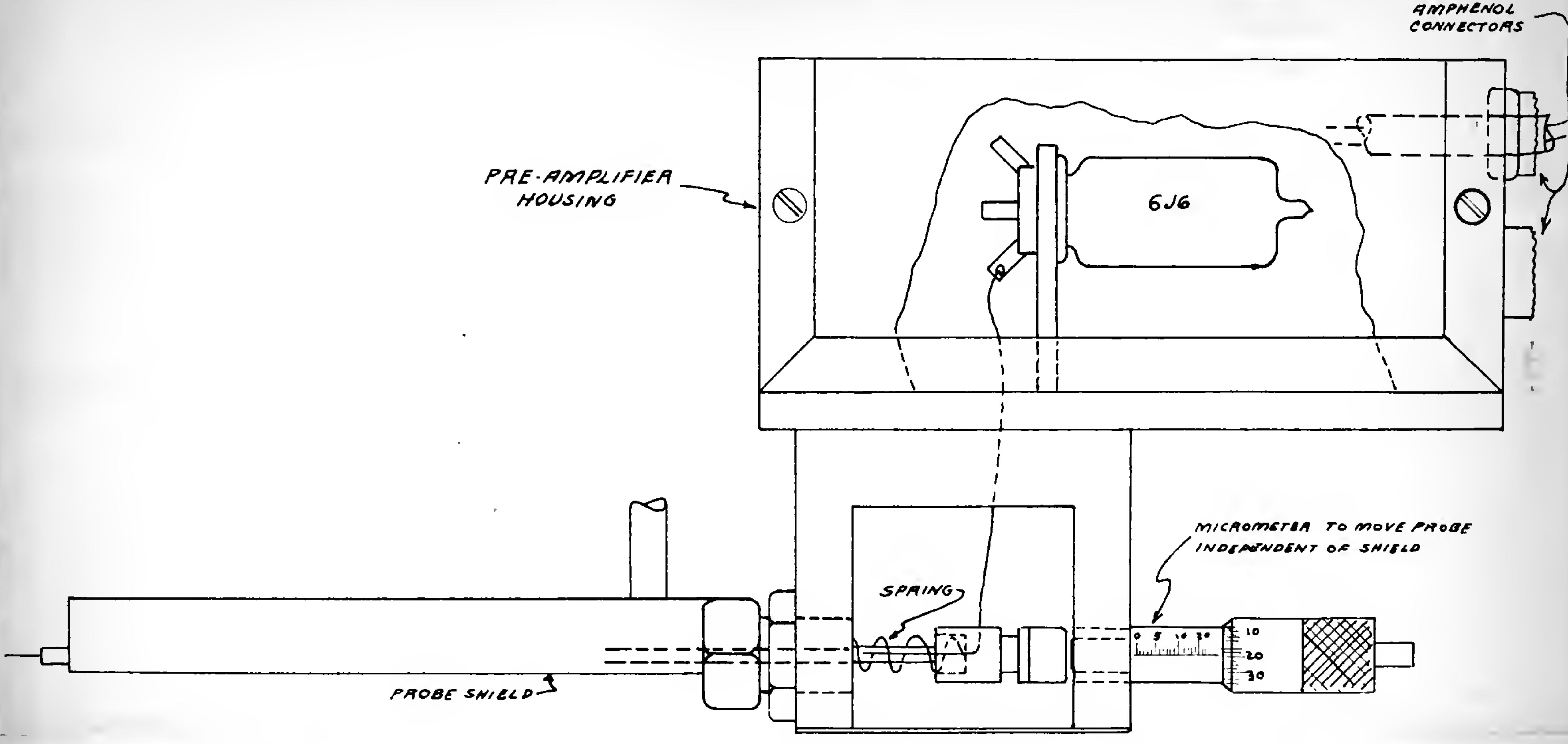
SCALE: 1"=1"

WATER-COOLED ELECTRONIC PROBE

(RE-DRAWN FROM BUMINES PRINT)

FIG. 3

12-2-54 JBC

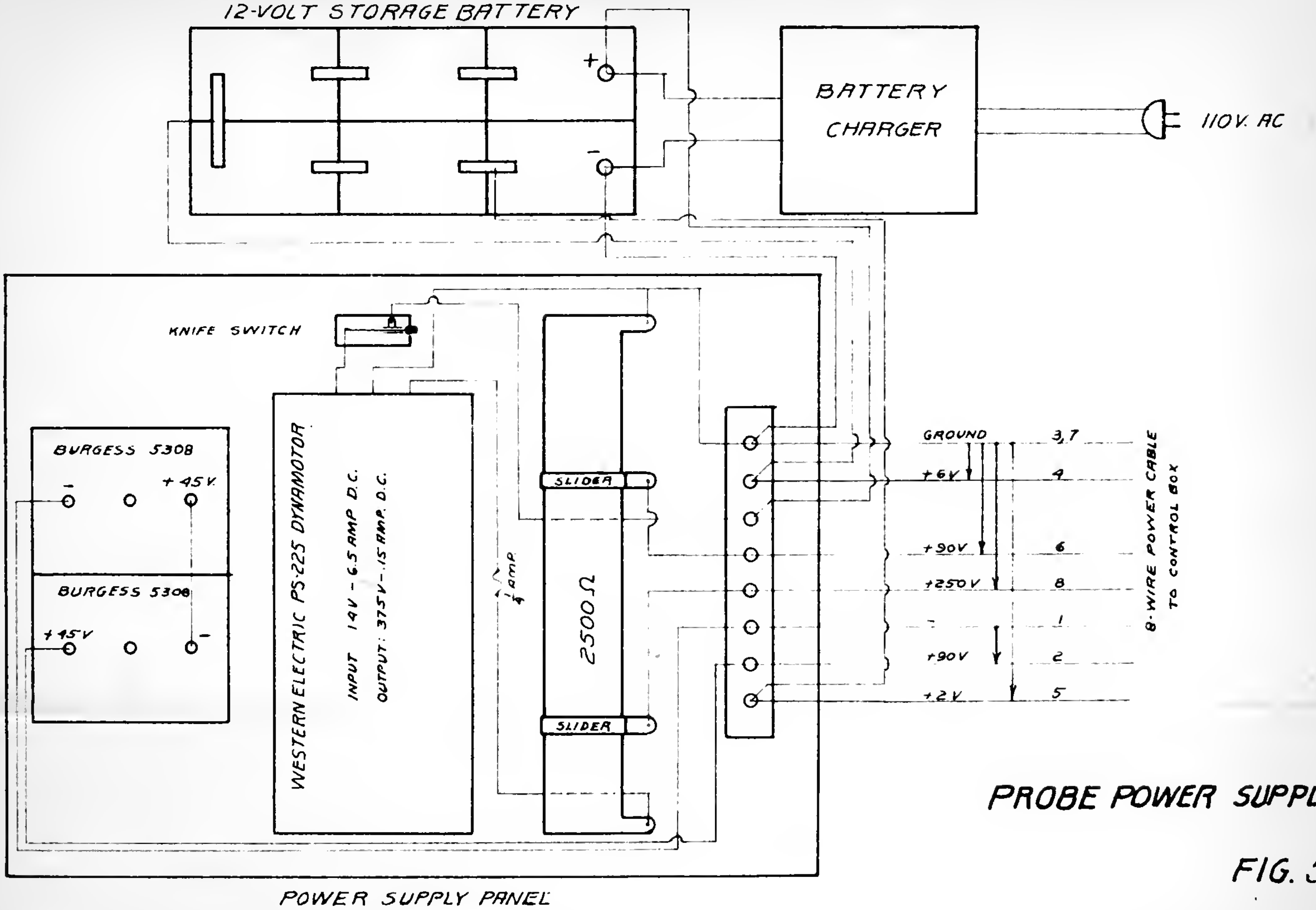


GENERAL PROBE ASSEMBLY

(TRACED FROM BUMINES PRINT B-1110)

FIG. 4

12-3-54 JBC



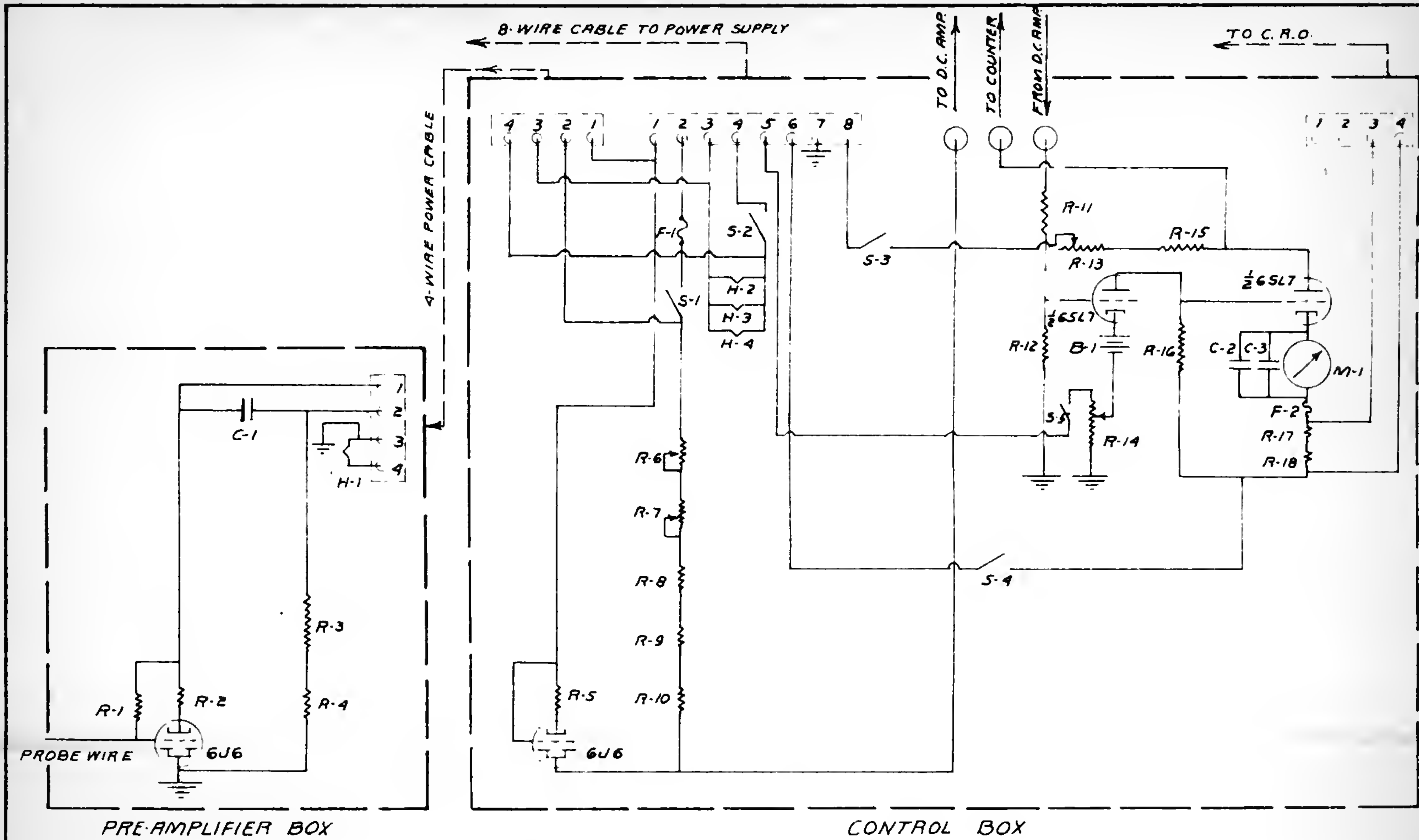
PROBE POWER SUPPLY

FIG. 5

4-13-55 JBC

LEGEND FOR PROBE WORKING DIAGRAM, FIGURE 6

B-1	1.5 volt bias battery
C-1	20 microfarad
C-2	4000 microfarad
C-3	4000 microfarad
F-1	10 milliampere fuse
F-2	5 milliampere fuse
H-1	6J6 heater (preamplifier box)
H-2	6J6 heater (control box)
H-3	1/2 6SL7 heater
H-4	1/2 6SL7 heater
M-1	0-3 milliammeter
R-1	0.47 megohm
R-2	500 ohm
R-3	4700 ohm
R-4	300 ohm
R-5	500 ohm
R-6	1000 ohm potentiometer (control box knob No. 3)
R-7	25 ohm potentiometer (control box knob No. 2)
R-8	2700 ohm
R-9	1000 ohm
R-10	800 ohm
R-11	51 kilohm
R-12	0.47 megohm
R-13	25 kilohm potentiometer (screwdriver adjustment on control box)
R-14	6 ohm potentiometer (knob No. 1 on control box)
R-15	15 kilohm
R-16	47 kilohm
R-17	200 ohm
R-18	300 ohm
S-1	90-volt battery switch (switch No. 2 on control box)
S-2	Heater switch (switch No. 1 on control box)
S-3	250-volt on-off tube plate supply switch (switch No. 3 on control box)
S-4	90-volt height discriminator plate supply switch (switch No. 2 on control box)
S-5	2-volt bias battery switch (switch No. 1 on control box)

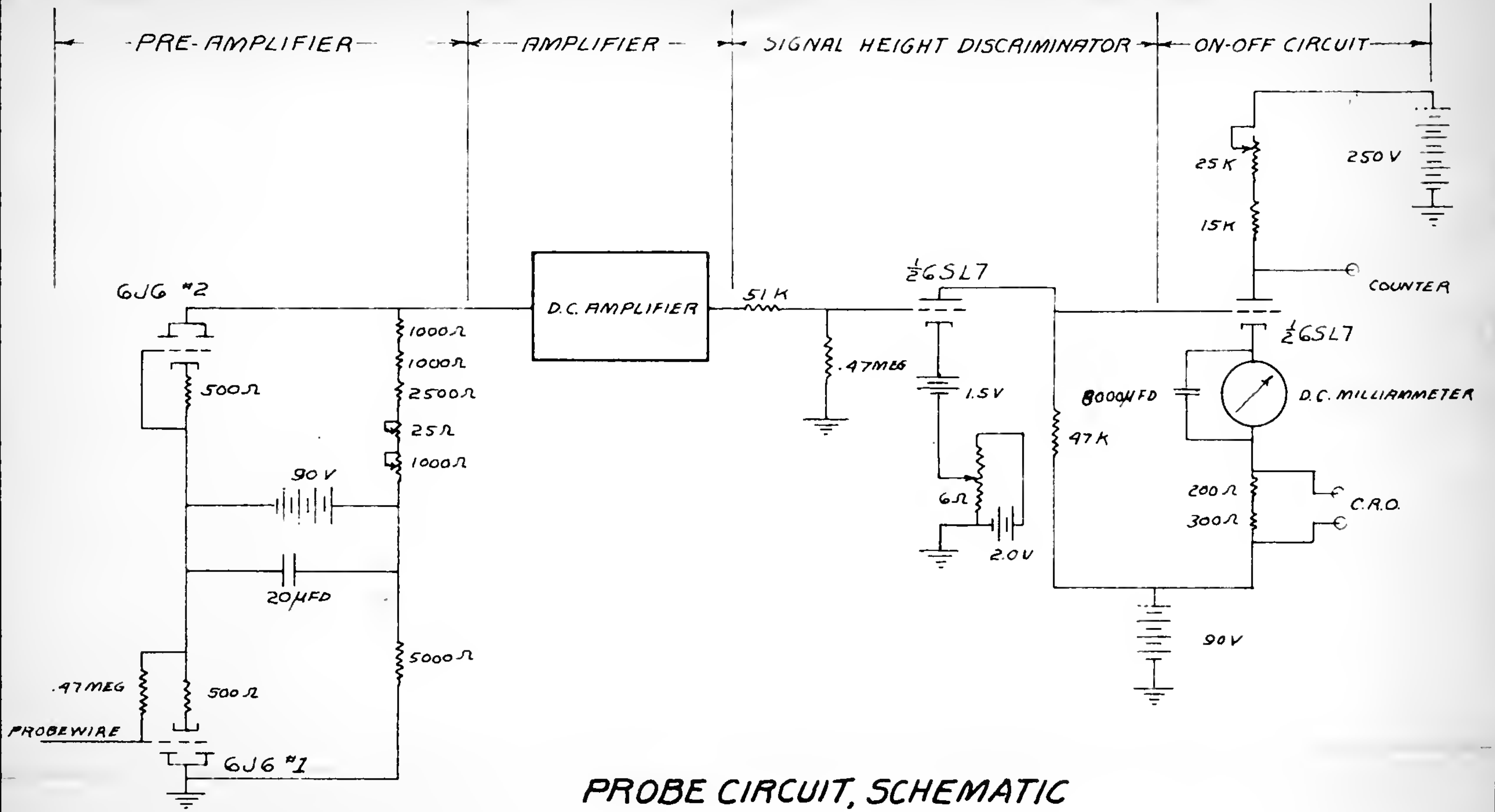


PROBE WORKING DIAGRAM

FIG. 6

NOTE: SEE NEXT PAGE FOR LEGEND

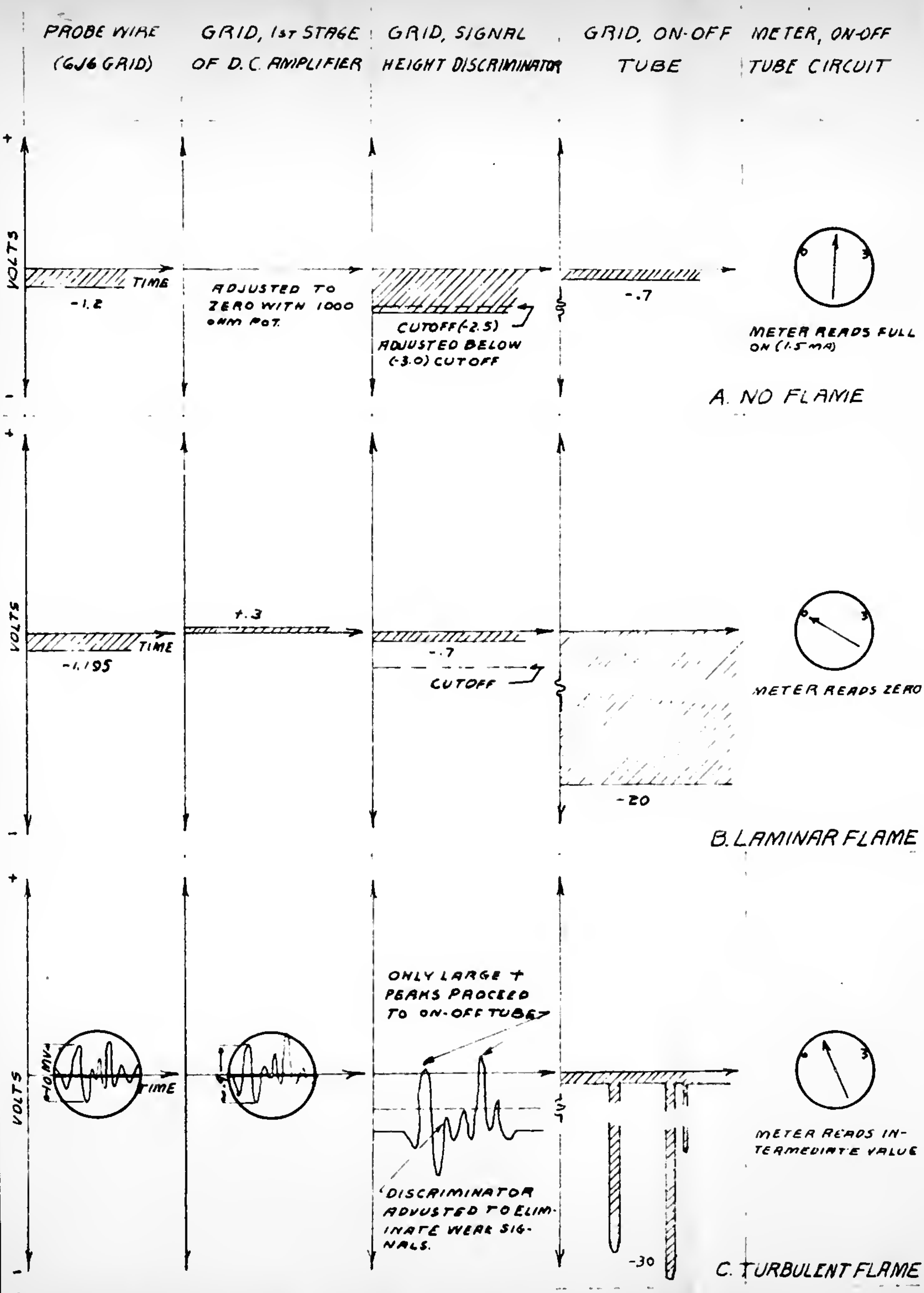
4-14-55 JBC



PROBE CIRCUIT, SCHEMATIC

FIG. 7

4-15-55 JBC



SIGNAL ANALYSIS, THREE OPERATING CONDITIONS

FIG. 8

5-7-55 JBC

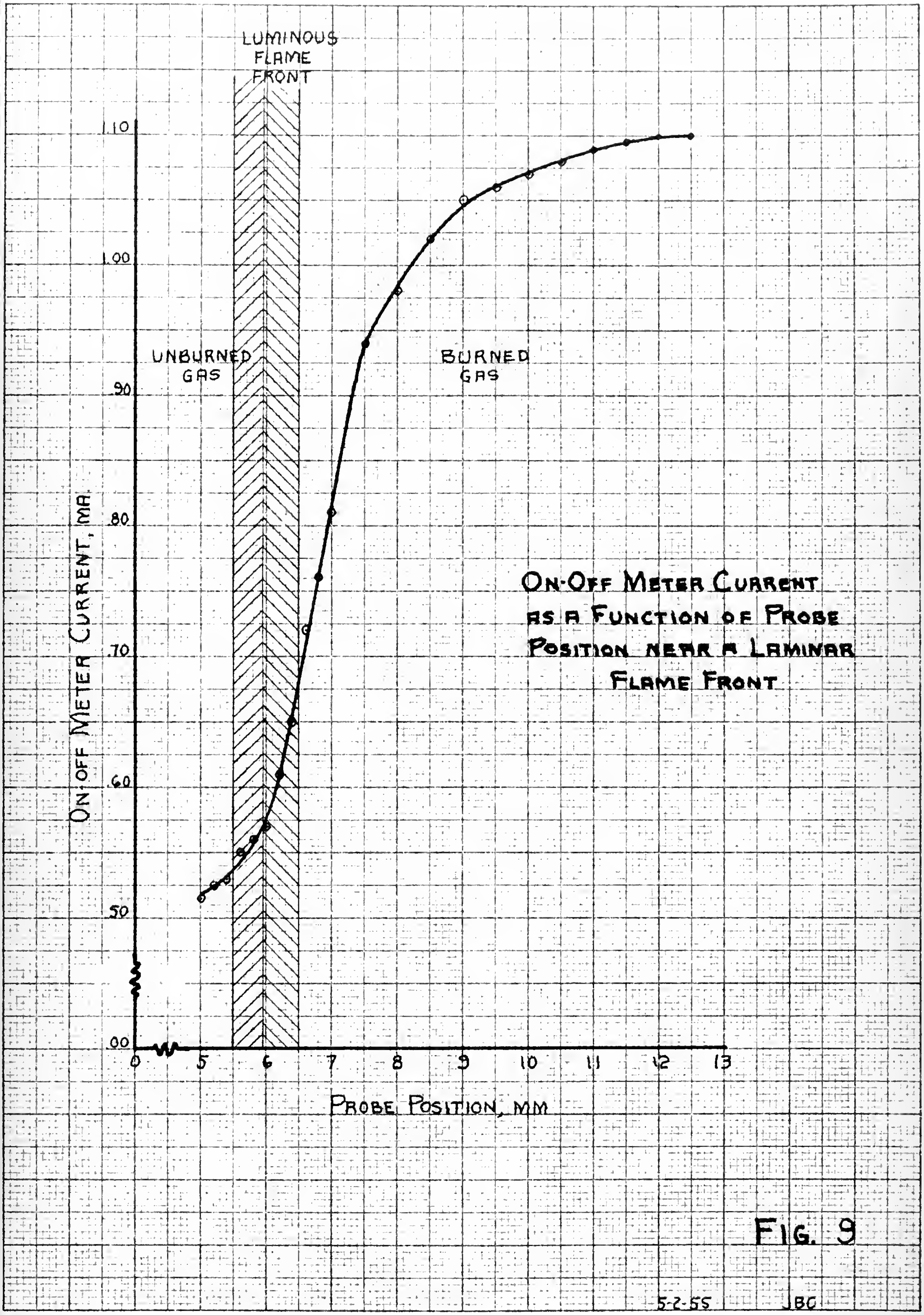


FIG. 9

5-2-55 JBC

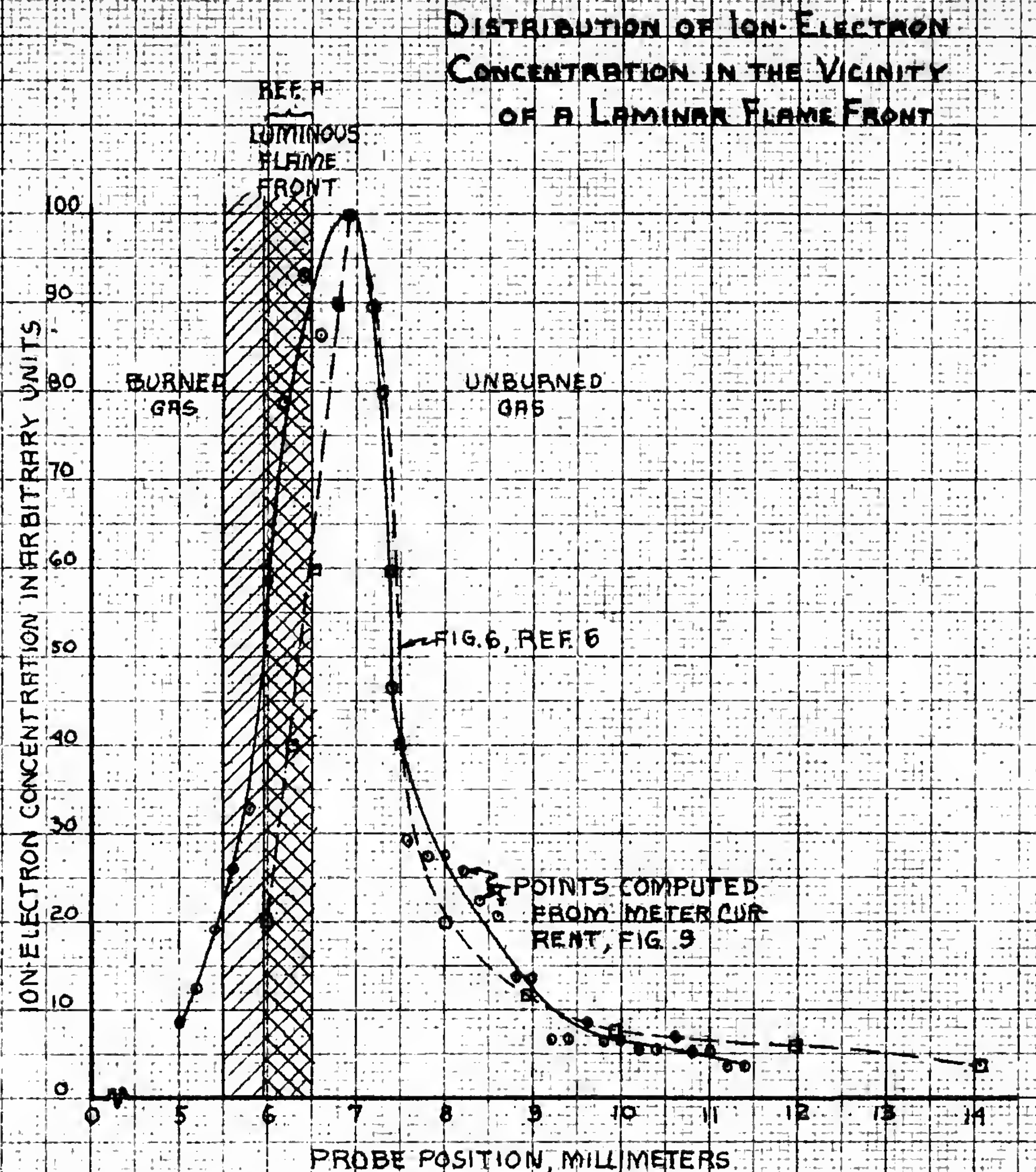


FIG. 10

5-4-55 JBC

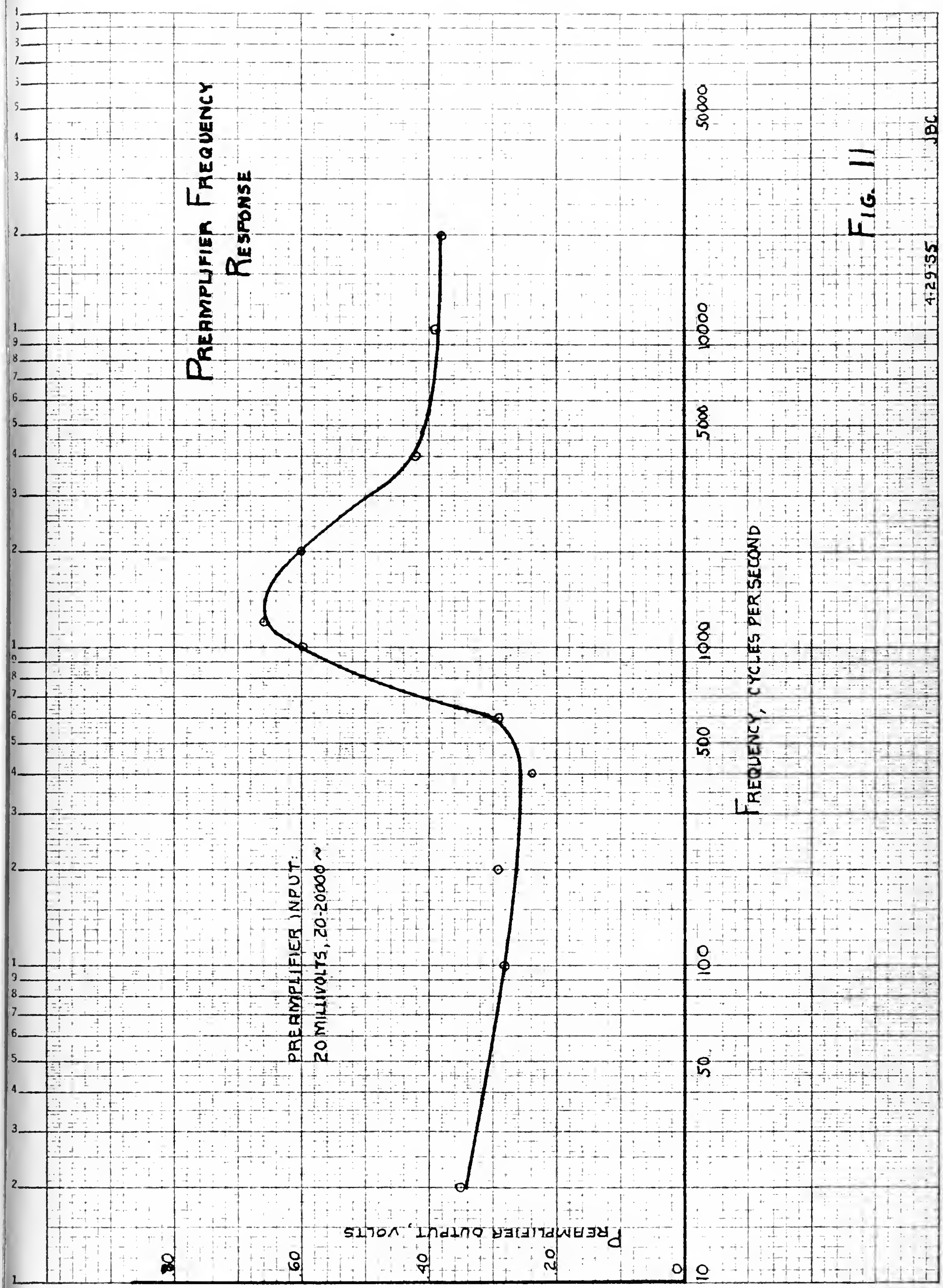
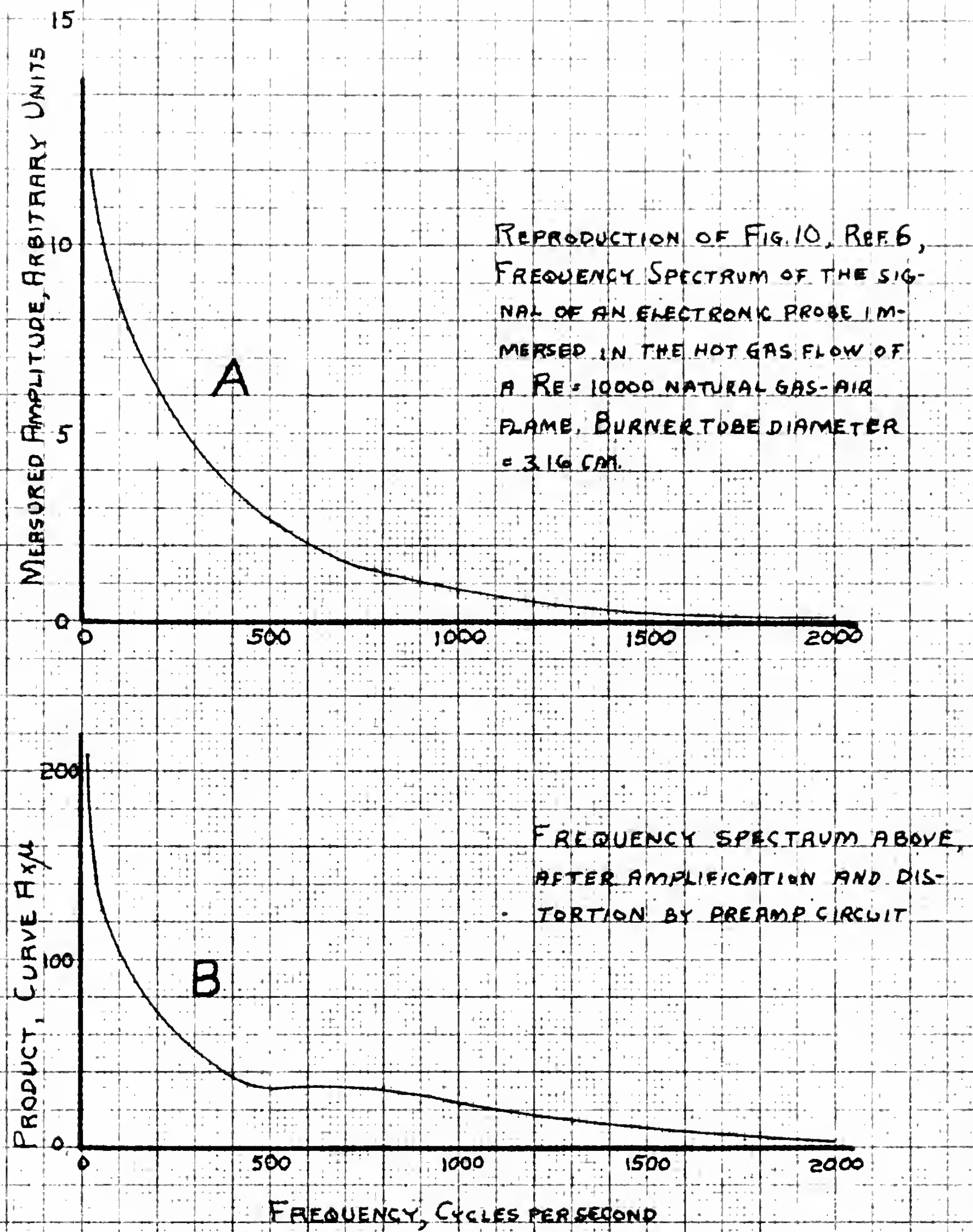

PREAMPLIFIER FREQUENCY RESPONSE
PREAMPLIFIER INPUT:
20 MILLIVOLTS, 20-20000 ~
FREQUENCY, CYCLES PER SECOND
10
50
100
500
1000
5000
10000
50000
PREAMPLIFIER OUTPUT, VOLTS
0
20
40
60
80
4-29-55
JBC

FIG. 11

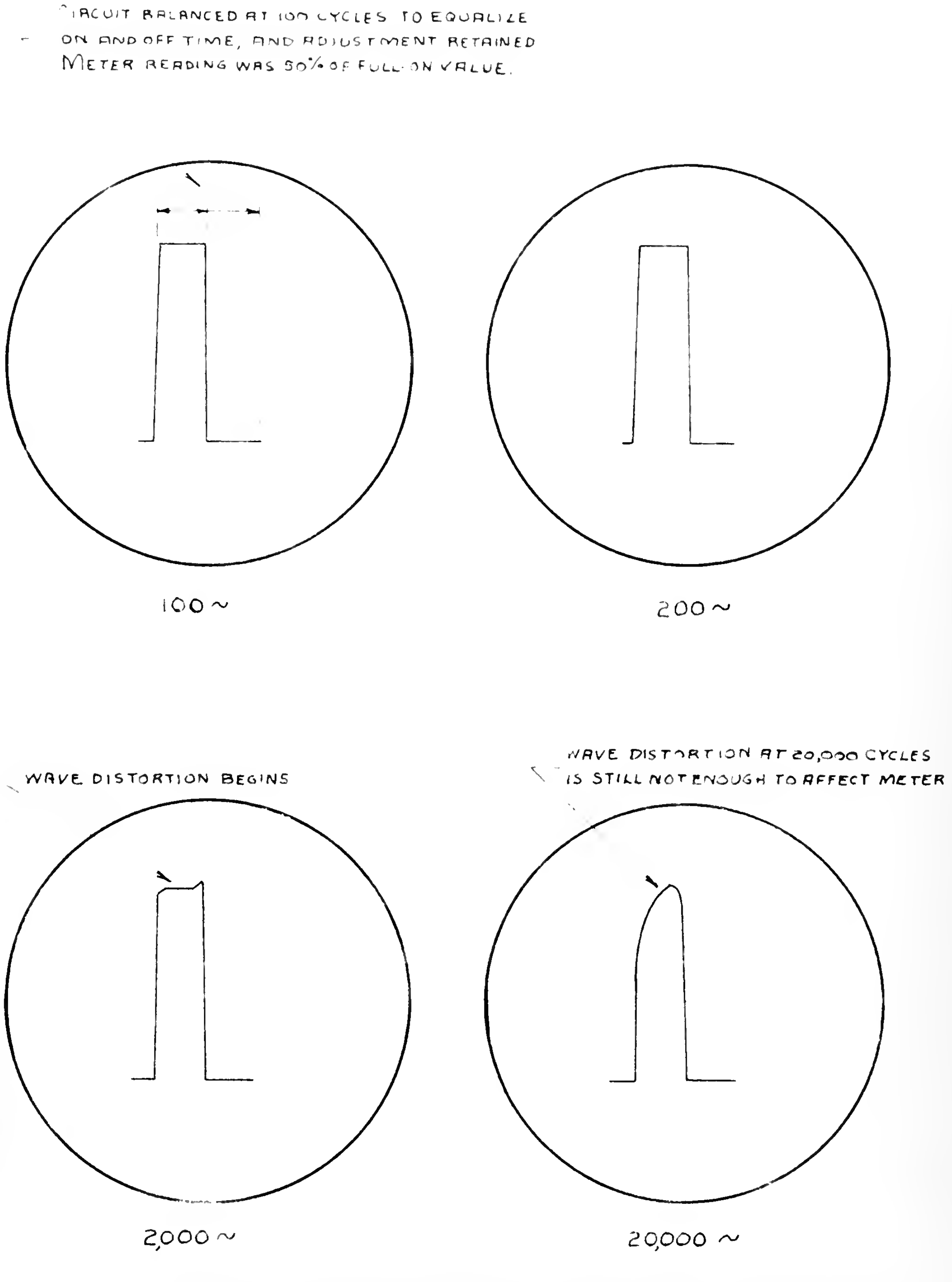


NOTE: $\mu \equiv \dfrac{\text{ORDINATE, FIG. 11}}{020}$

EFFECT OF NON-LINEAR PREAMPLIFIER RESPONSE ON A KNOWN FREQUENCY SPECTRUM

FIG. 12

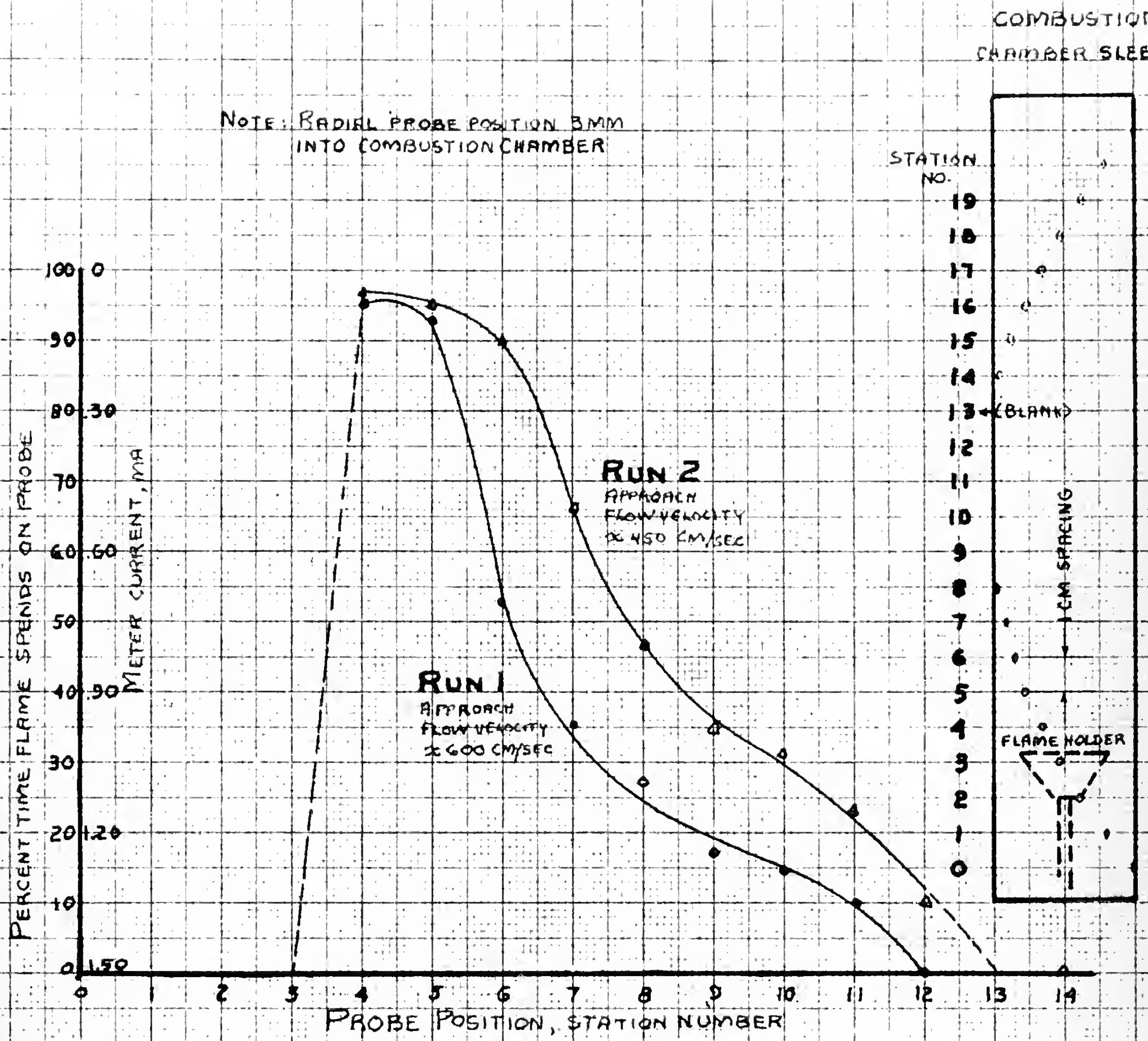
4-30-55 JBC



ON-OFF TUBE CURRENT AT SEVERAL FREQUENCIES

FIG. 13

5-6-55 JBC



STATION	METER RUN 1	METER RUN 2
0	—	—
1	—	—
2	—	—
3	1.50	1.50
4	.07	.05
5	.11	.08
6	.70	.15
7	.97	.50
8	1.09	.80
9	1.24	.98
10	1.28	1.03
11	1.35	1.15
12	1.50	1.35
14	—	1.50

FLAME LENGTH ALONG COMBUSTION CHAMBER WALL

FIG. 14

5-2-55 180